Renewable Energy 95 (2016) 178–190

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Comparative analysis of the infield response of five types of photovoltaic modules

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A R T I C L E I N F O

Article history:
Received 31 December 2015
Received in revised form
2 March 2016
Accepted 1 April 2016
Available online 13 April 2016

Keywords:
Infield photovoltaic response
Photovoltaic output
Photovoltaic efficiency
BIPV

A B S T R A C T

Five types of photovoltaic (PV) modules were comparatively analyzed considering the electrical output, efficiency and relative loss in efficiency, based on infield data collected in a temperate mountain climate, over 14 months. The mono-, poly-crystalline silicon, CdTe, CIS and CIGS modules were mounted on two identical platforms, installed close to a row of buildings. Based on the data collected from individual or groups of modules on the two platforms, analyses focused on the photovoltaic output, considering: the mean monthly values; the influence of the neighboring buildings; the influence of the irradiance, temperature and wind in different seasons (winter, summer); the influence of tracking on each PV module type. The qualitative analysis shows that small PV platforms installed in the built environment require accurate investigations on the air currents with influence on snow and frost retention/melting and water vapor condensation. In the temperate climate, with snowy winters and rather warm summers, the best performing modules are of poly-crystalline silicon; among thin film modules, the best output corresponds to CIGS, while the steadiest efficiency corresponds to CdTe. Tracking has a "leveling" effect on the conversion efficiency, making the PV output more predictable during days with preponderant direct solar irradiance.

1. Introduction

Extended research is devoted to estimate the photovoltaic infield conversion efficiency as a prerequisite for accurate design of feasible and affordable systems; literature outlines that the main factors affecting the conversion efficiency are: the PV type/materials, the amount of incident solar irradiance and the operating temperature [1,2]. These factors are further depending on specific features of the implementation location (geographical coordinates, climatic profile) and on parameters such as the ambient and PV module temperature variation with wind, etc.

The infield conversion efficiency is important in the output prediction for an adequate balance of system, BOS. Additionally, the correct estimation of the electricity production represents a bottleneck in the feasible exploitation of PV systems, as in several countries a 24 h advance is set for selling the next day PV production; any overproduction is not part of the trade, while any under-estimation is penalized. Therefore, prediction algorithms are developed and a recent analysis shows that there is no need for complex models if reliable calibration data are available [3].

The accurate knowledge on the photovoltaic response is time consuming, as reliable data are required for at least one full year of monitoring; therefore, there is a need for analyzing infield data of various PV module types, and outline novel findings/correlations for typical locations.

An important application of PV systems is the built environment. In the near future, new and existing buildings have to meet strict energy consumption standards in order to comply with the nZEB (Nearly Zero Energy Building) status, which implies that a building produces at least 50% of its energy demand using renewables installed on or nearby. Photovoltaics are main candidates, installed on suitably oriented roofs, rooftops, façades or individual arrays. Hereby, one constraint is related to the available area for PVs mounting, thus the system design requires accurate estimation of the infield efficiency, supporting the selection of best performing PV modules in the implementation location and the PV array dimensioning [4].

Literature addresses the variation in the conversion efficiency of different PV technologies implemented in the built environment

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http://dx.doi.org/10.1016/j.renene.2016.04.003
0960-1481/

[5,6], but recommendations on the best PV module type(s) for a given climatic profile are scarce.

The analysis of different PV types using mathematical models can be used. Three PV types (mono-, poly-crystalline and amorphous silicon) were analyzed [7] covering the materials physics and the cost analysis; simulations based on meteorological data are reported [8], to define the behavior of four PV types: amorphous silicon (a-Si), tandem structure of amorphous silicon and microcrystalline silicon, CdTe and polycrystalline silicon (p-Si).

More accurate is the infield testing of different installed PV types; usually papers analyze no more than three PV types, as the comparative analysis of monocrystalline silicon (m-Si), p-Si and CdTe [9], or the study on p-Si, a-Si, and heterojunction with intrinsic thin layer (HIT), [10]. A comparative analysis of eight PV parks (with p-Si, a-Si, CdTe, GaAs or HIT modules) was recently reported concluding on the infield output and on the enhancement brought by tracking [11]. The PV modules reported in these papers are mainly serially connected, when a defect or lower-rated module will influence the result of the entire string. This solution also limits the possibility to compare modules of same type subjected to identical (PV mismatch) or different (shading) conditions [12].

Based on infield data collected over 14 months, this paper comparatively analyses the photovoltaic response of five PV module types (p-Si, m-Si, CIGS, CdTe and CIS); each module/group of modules has a power optimizer, further connected to an inverter. This setup allows to individually monitor the delivered power, thus the conversion efficiency and the relative losses. Two identical platforms are implemented in the built environment allowing comparison on the average output and on the deviations, correlated with specific features in the mountain temperate climate.

2. Experimental set-up

The experimental set-up is installed in a mountain temperate climate region (Brasov, Romania, 45.65°N, 25.65°E, 600 m above the sea level); the data were collected between July 2014 and August 2015.

A *Solys2* tracking system (Kipp & Zonen) measured the solar irradiance; it consists of a ball-shaded pyranometer for the diffuse solar irradiance (CMP22, ISO Secondary Standard, 1% daily uncertainty) and a pyrheliometer for the direct solar irradiance (CHP1, ISO First Class, 1% daily uncertainty). A *DeltaT* weather station measured the ambient temperature (RHT2 sensor, 0.1 °C accuracy), relative humidity (±2% accuracy), wind direction (WD1 wind vane, ±2° accuracy) and wind speed (AN1 anemometer, 1% accuracy). Sensors (PT100) are mounted on the back of each module for temperature monitoring.

Five different PV module types were used: p-Si and m-Si (noted as “poli” and, respectively “mono” in the graphs), and the thin film CIGS, CdTe and CIS; the parameters measured in standard testing conditions (STC) are given in Table 1. The thin-film modules were parallel connected, in groups of two (CIGS and, respectively CIS) or three modules (CdTe) to get a power similar to that of the silicon-based ones. The electrical output parameters of the photovoltaic modules are monitored for each module/group of modules using *Solaredge* components (a SE2200 single-phase inverter and P405 power-optimizers; accuracy of 2.5% in voltage and current). At least 7 power-optimizers are required to fit the nominal voltage of the invertor, therefore an array design was chosen consisting of 2 independent p-Si, 2 independent m-Si modules, 1 group of two parallel CIGS modules, 1 group of three parallel CdTe modules and 1 group of two parallel CIS modules, Table 1.

This array design (Fig. 1) was replicated on two identical platforms, P2 and P4, to test possible deviations in the output energy.

The platforms are part of a larger outdoor experimental set-up, Fig. 2, consisting of five platforms (P1 … P5), installed near the 12 laboratory buildings of the R&D Institute of the Transilvania University of Brasov. The P1, P3 and P5 platforms have only m-Si and p-Si modules.

The site has low wind potential with a predominant SE direction, with the strongest winds coming from W and NW, [13]. The laboratory buildings are developed as nZEB, with metallic coverage high insulating façades; the S-facing façades heat faster thus may generate air currents that can influence the PV output. These local currents are close to the ground and are not sensed by the anemometers on the weather station, thus are not part of the wind rose

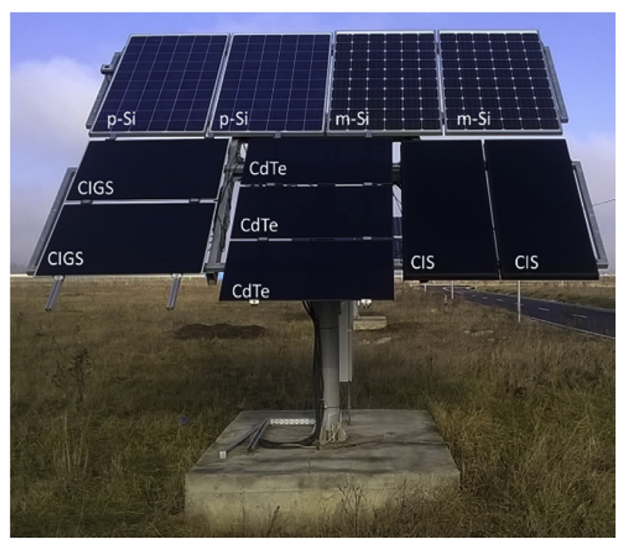

Fig. 1. Platform P2 with five types of PV modules.

Table 1
Standard testing conditions (STC) parameters of the five types of photovoltaic modules.

	p-Si	m-Si	CIGS	CdTe	CIS
Manufacturer	LDK	Heliene	Solibro	Calyxo	Avancis
Product code	LDK-250P-20	HEE215M	SL2-120	CX3 80	Powermax Strong 125
Peak power P_{max} [W]	250 (±3%)	250 (±3%)	120 (+4%)	80 (±5%)	125 (+4%)
Maximum voltage Vm [V]	30.2	30.8	76.9	47.0	43.8
Maximum current Im [A]	8.28	8.12	1.56	1.72	2.85
Open circuit voltage Voc [V]	37.5	37.4	97.6	62.8	59.1
Short circuit current Isc [A]	8.59	8.67	1.69	2.01	3.24
Nominal Efficiency [%]	17.12	17.94	13.54	11.89	13.04
Photovoltaic area of a module [m^2]	1.46	1.39	0.89	0.673	0.96
STC temperature coefficient of P_{max}, Eq. (7) β [$°C^{-1}$]	0.0045	0.0044	0.0038	0.0025	0.0039
No. of modules in a group	1	1	2	3	2
No. of modules on a platform	2	2	2	3	2